Evaluation of a Biaxial Ice Stress Sensor

by

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ABSTRACT

Controlled laboatory tests were performed to evaluate the response of a cylindrical, biaxial ice stress sensor. The tests demonstrate that the sensor has a low temperature sensitivity (5 kPa/°C) and is not significantly affected by differential thermal expansion between the ice and gauge. Loading tests on fresh water and saline ice blocks containing the embedded sensor show that the sensor has a resolution of 20 kPa and an accuracy of better than 15% under a variety of uniaxial and biaxial loading conditions.

INTRODUCTION

Reliable, inexpensive ice stress measurements are needed to solve a variety of ice related problems. These include: measuring and monitoring ice loads on marine and hydraulic structures; determining the magnitude of ice forces associated with ice drift, ride-up, pile-up and pressure ridge formation; measuring thermal ice pressures in reservoirs; and assessing the effects of ice convergence on the performance of large icebreakers and tankers.

During the past several years, a biaxial ice stress sensor has been under development at Oceanographic Services, Inc., CRREL, and IRAD Gage, Inc. (Johnson and Cox, 1980; Johnson and Cox, 1982; and Cox and Johnson, 1983). This paper summarizes the results of controlled laboratory tests which were performed to evaluate the new biaxial gauge. More detailed information on measuring stress in ice, the biaxial sensor theory, and the laboratory results are given in Cox and Johnson (1983).

BIAXIAL ICE STRESS SENSOR

The biaxial ice stress sensor consists of a stiff cylinder made of steel (Fig. 1 and 2). It is 20.3 cm long, 5.7 cm in diameter and it has a wall thickness of 1.6 cm. The ends of the sensor are threaded such that a rounded end cap can be attached to the lower end of the sensor. Extension rods can also be screwed to the top of the sensor to position the sensing portion of the gauge at any desired depth in the ice sheet.

Principal ice stresses normal to the axis of the gauge are determined by measuring the radial deformation of the cylinder wall in three directions. This is accomplished by use of vibrating wire technology advanced

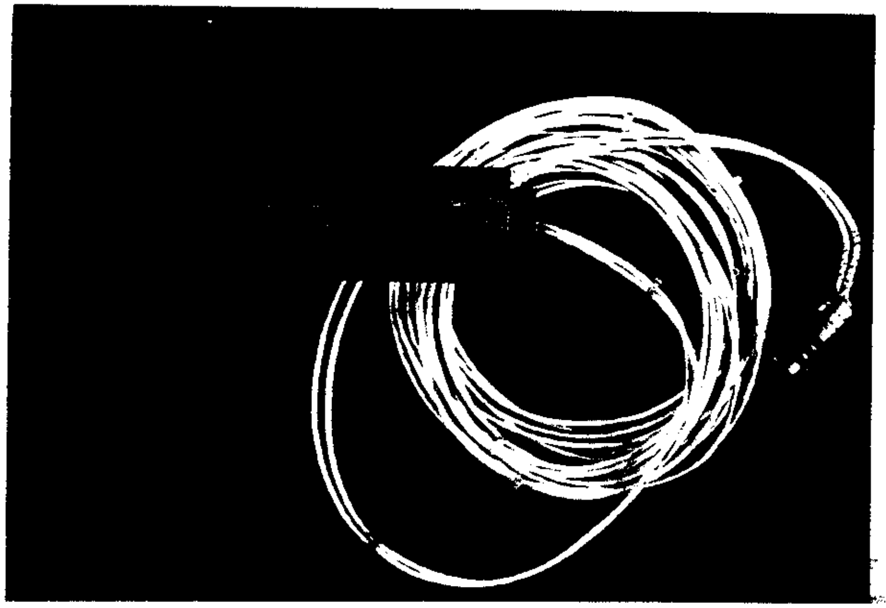


Figure 1: Biaxial ice stress sensor.

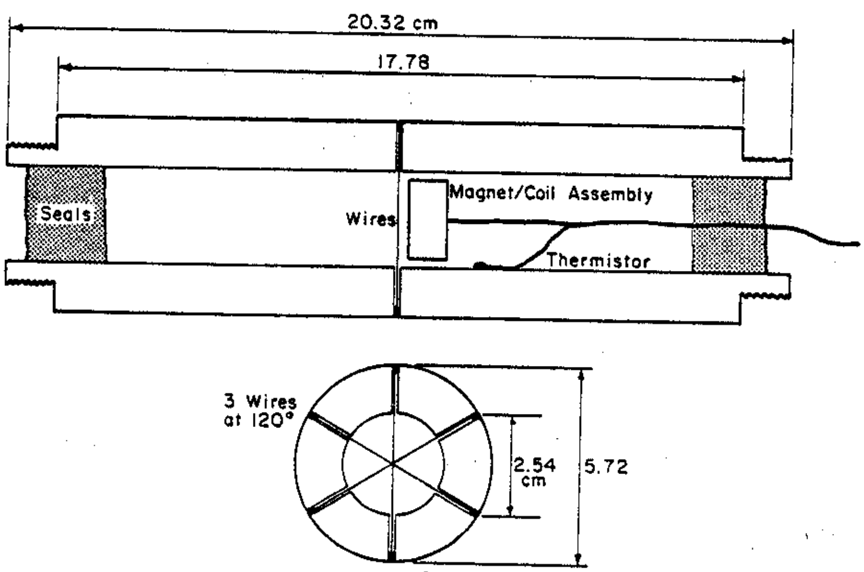


Figure 2: Schematic of biaxial ice stress sensor.

by IRAD Gage (Hawkes and Bailey, 1973). Three tensioned wires are set 120° from each other across the cylinder diameter (Fig. 2). The diametral deformation of the gauge in these three directions is determined by plucking each wire with a magnet/coil assembly and measuring the resonant frequency of the vibrating wires. A thermistor is also placed inside the cylinder to measure the gauge temperature. Both ends of the sensor are sealed to protect the wires and electronics from moisture. The sensor and data logging equipment are fabricated by IRAD Gage in Lebanon, N.H.

Despite the stiffness of the gauge, it is very sensitive to loading. Radial displacements as small as 5.0×10^{-3} μm (2.0×10^{-7} in.) can be measured. This corresponds to a sensor resolution of about 20 kPa (3 lbf/in.^{2}) when it is embedded in ice.

This design offers several advantages. The sensor is rugged and leakproof and it can be easily installed in the ice using conventional ice augering equipment. As the sensor output is frequency, it is not affected by leakage to ground, poor contacts and long lead lengths. The sensor is also inexpensive ($1700 for the prototype, including labor and materials).

The magnitude and direction of the principal stress (p, q, and θ_1) are calculated from the radial deformation (V_{r1}, V_{r2}, and V_{r3}) of the sensor wires by solving three simultaneous equations:

$$V_{r_1} = A\,(p+q) + B\,(p-q)\cos 2\,\theta_1$$

$$V_{r_2} = A\,(p+q) + B\,(p-q)\cos 2\,(\theta_1 + 60°)$$

and

$$V_{r_3} = A\ (p+q) + B\ (p-q)\ \cos 2\ (\theta_1 + 120°)$$

where A and B are constants which depend on the gauge geometry and the mechanical properties of the ice and gauge. The sensor is designed such that A and B are relatively insensitive to variations in the ice modulus, E_i, and Poisson's ratio, υ (Fig. 3 and 4). Equations for A and B are given in Cox and Johnson (1983). They are derived from analytical solutions which describe the behavior of an elastic ring welded in an elastic plate (Savin, 1961).

The biaxial ice stress sensor is not calibrated in ice. It is calibrated in a hydraulic pressure cell to determine the initial frequency and the effective length of each vibrating wire. The gauge is radially loaded and the measured deformation of the gauge is compared to the radial deformation of a thick-wall cylinder.

EVALUATION TESTS

Controlled laboratory tests were performed to evaluate the biaxial ice stress sensor. Tests were first conducted to determine the temperature sensitivity of the gauge. The sensor was then frozen into large ice blocks and loaded in a biaxial loading machine to study the response ofthe sensor under different loading conditions. The effects of differential thermal expansion between the sensor and surrounding ice and long-term sensor drift were also examined.

Temperature Sensitivity

The temperature sensitivity of the gauge was determined by placing the sensor in a glycol bath inside an environmental chamber. The temperature of the chamber and bath were varied and sensor readings were taken at

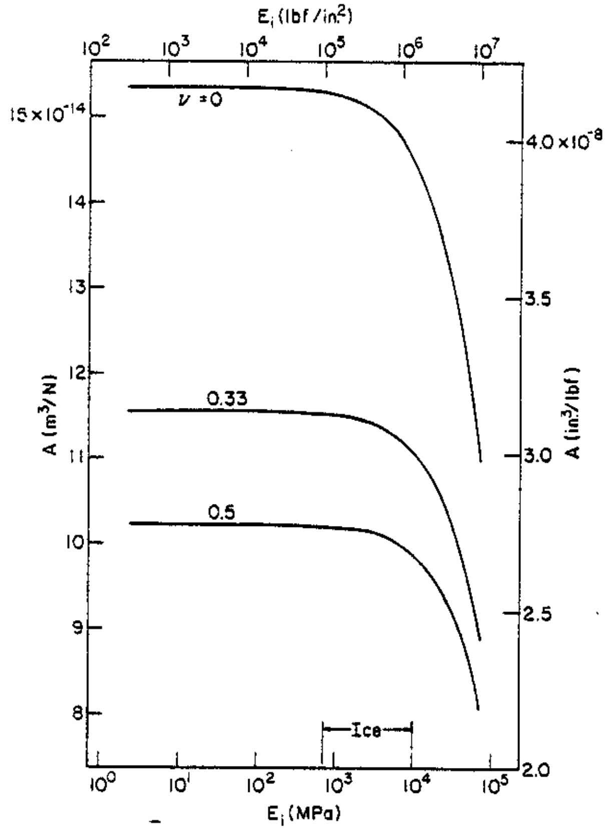


Figure 3: Variation of A with ice moduli.

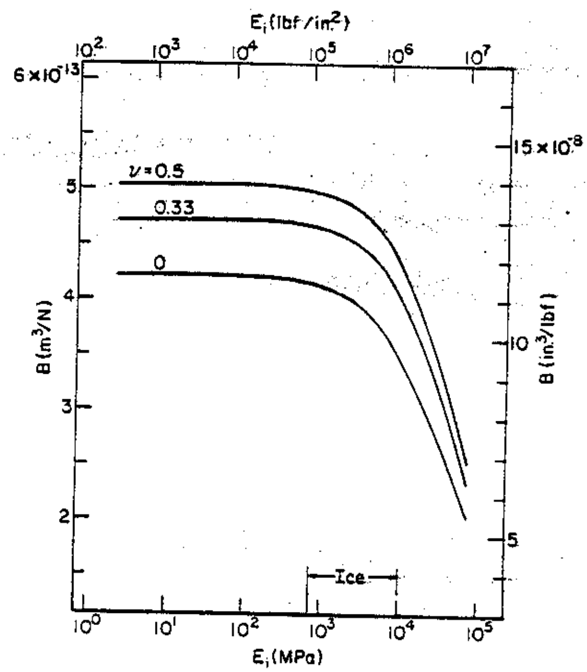


Figure 4: Variation of B with ice moduli.

different temperatures. The results for each of the three vibrating wires in the gauge are presented in Figure 5.

Biaxial Loading Tests

The response of the sensor to different loads was evaluated by freezing the sensor into large ice blocks and loading the blocks in a hydraulic, biaxial loading machine. The ice blocks used in these tests were 61 cm x 61 cm x 18 cm thick. The length and width of the ice blocks were chosen to accommodate the entire area of influence of the sensor, about ten diameters.

The blocks were grown from both fresh and saline water. The grain size of the crystals in the blocks varied between 0.5 and 2 cm. The fresh water blocks had both horizontal and vertical c-axis crystals, while the saline ice blocks had predominantly horizontal c-axis crystals. The c-axis did not show any preferred alignment in the horizontal plane. The saline ice blocks had an average salinity of about 5 o/oo.

The biaxial loading machine used in the stress sensor verification tests is shown in Figure 6. The machine consisted of two, 0.4 MN-capacity hydraulic rams supported by two independnet I-beam frames. The inside ram and frame rolled on casters to minimize shear stresses on the block during biaxial loading as well as to compensate for any lack of planar squareness of the ice blocks. The platens consisted of aluminum blocks covered with sheets of teflon. They were only 58 cm wide to allow for about 3 cm of block strain during a biaxial loading test. The platens were also free to rotate in the vertical plane to compensate for lack of end squareness of the ice blocks.

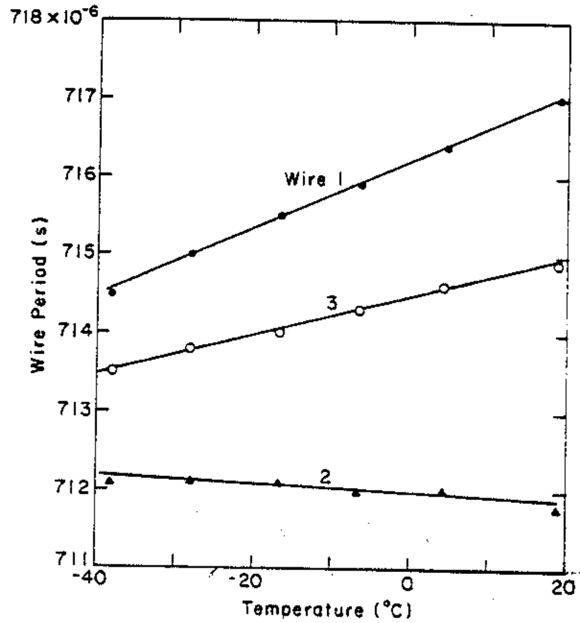


Figure 5: Variation of wire period with temperature for each of the three wires in the biaxial ice stress sensor.

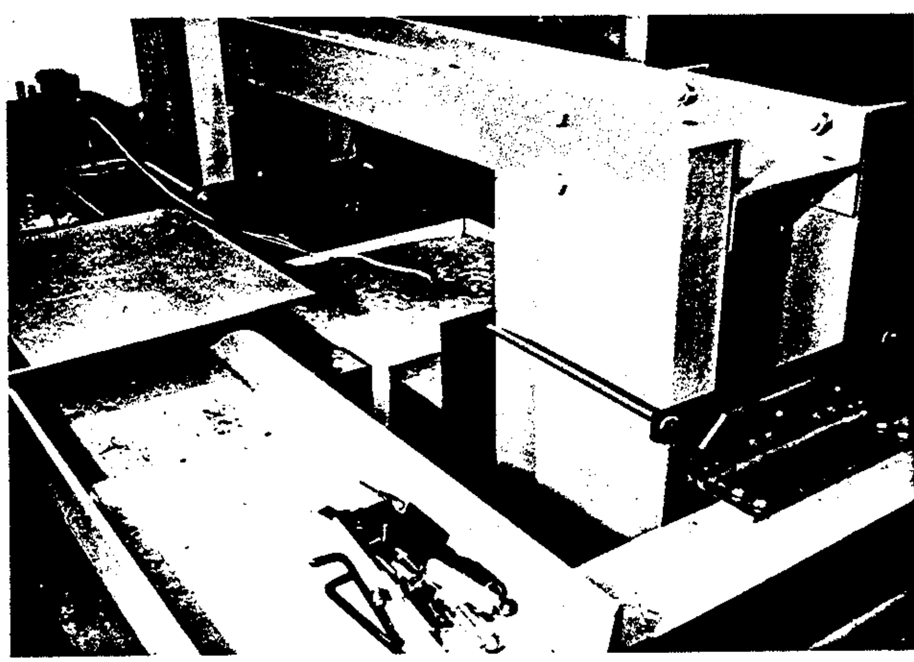


Figure 6: Ice block and sensor in biaxial loading machine.

Loads were applied to the ice blocks using the rams and a hydraulic hand pump. Control valves were used to direct the hydraulic fluid to one or both rams and a hydraulic dial gauge was used to measure the load. The entire loading system was calibrated with a load cell prior to testing. Applied uniaxial stresses on the ice blocks had an accuracy of about 20 kPa. In a few tests, block strains were measured with direct current distance transducers attached to the platens.

Four blocks were used in the loading tests. Blocks 1 and 2 were fresh water ice and blocks 3 and 4 were saline ice. Measured versus applied stress for each test are plotted in Figures 7 through 10. In calculating the measured stress from the diametrial deformation of the gauge, a modulus of 0.69 GPa and Poisson's ratio of 0.33 were assumed for the ice. This corresponds to coefficient A and B values of 1.15×10^{-13} and 4.74×10^{-13} m^3/N, respectively.

Differential Thermal Expansion

Block 4 was also used to study the effects of differential thermal expansion between the ice and gauge. To simulate conditions in the field where the sensor would be covered with an insulated instrument box, the block was insulated on the top and bottom with foam. The temperature of the sensor and block were then varied from -20°C to 0°C and back to -10°C to examine the response of the gauge. After the stress measurements were corrected for changes in temperature, the stress readings were generally within or equal to the resolution of the sensor, 20 kPa.

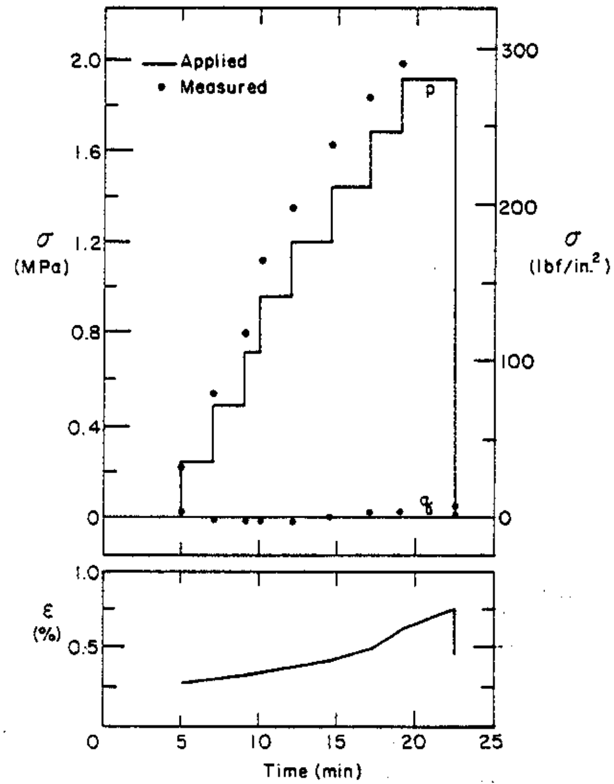


Figure 7: Measured versus applied stress and block strain for block 1.

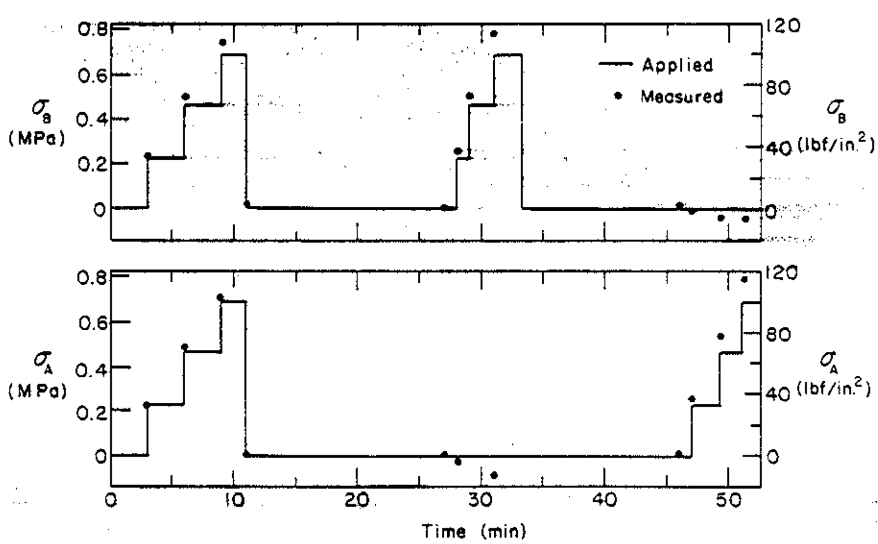
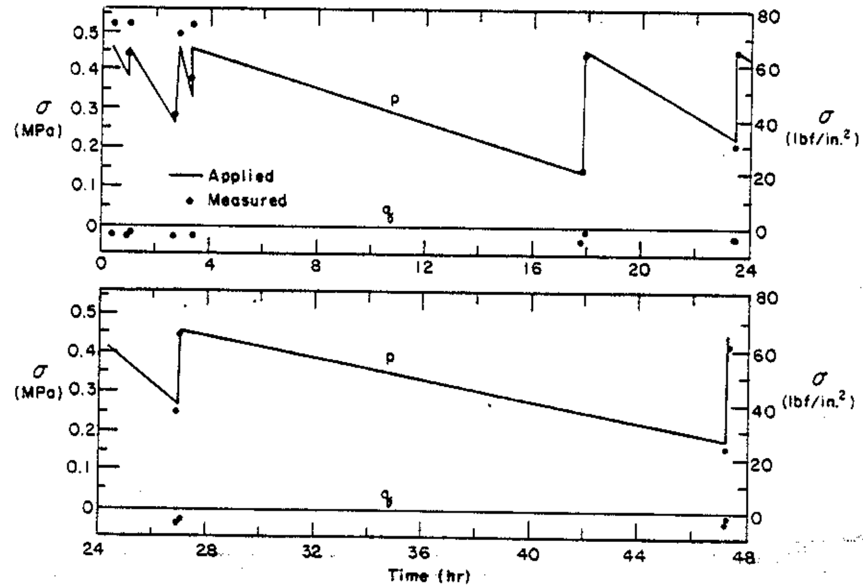
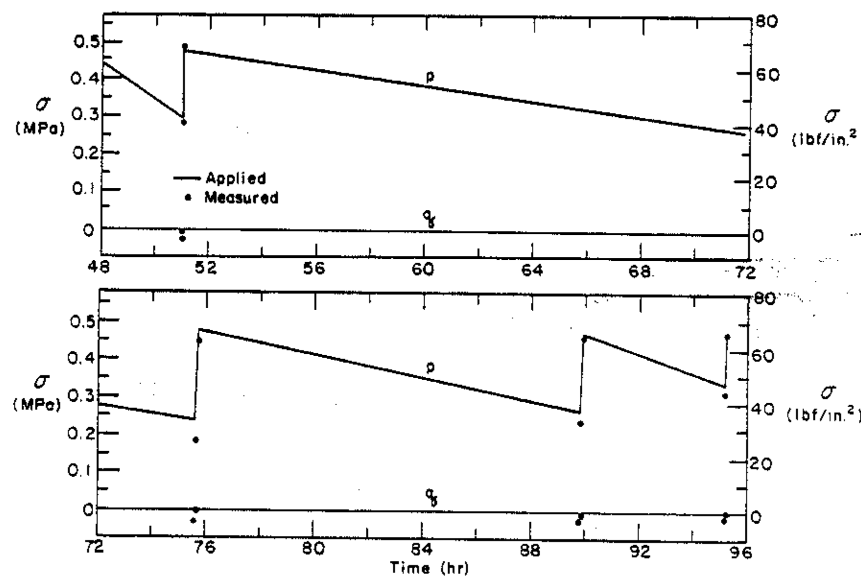


Figure 8: Measured versus applied stress in the two loading directions of block 2.

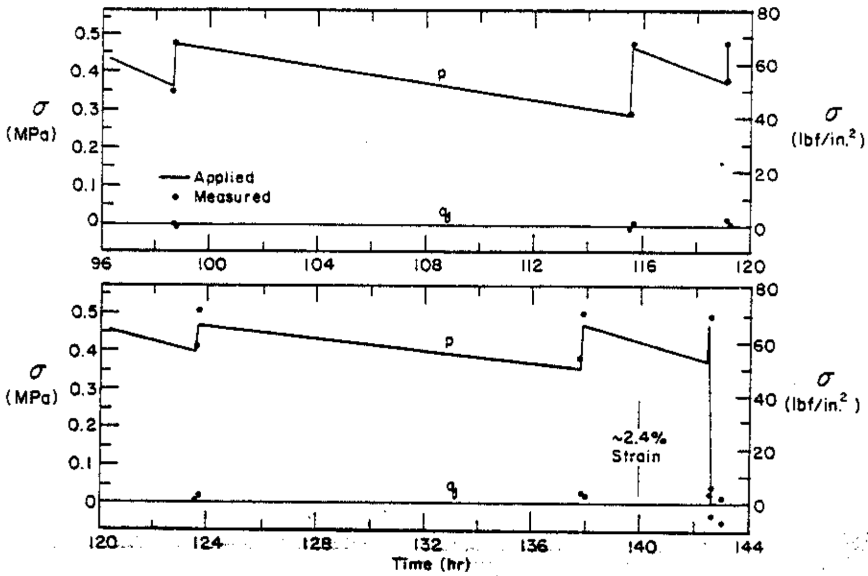


a. 0 to 48 hours.

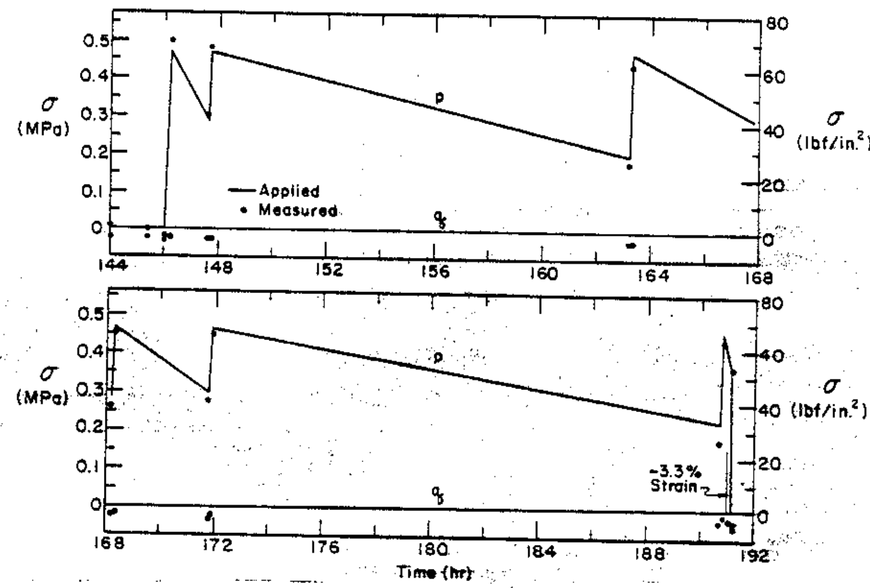


b. 48 to 96 hours.

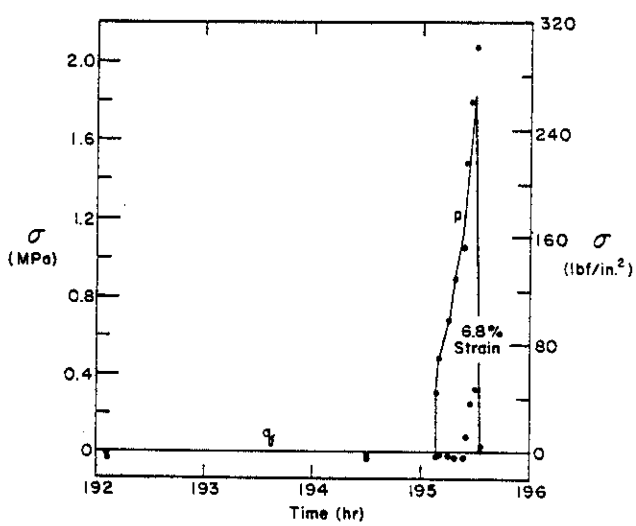
Figure 9: Measured versus applied stress for block 3.



c. 96 to 144 hours.



d. 144 to 192 hours.



e. 192 to 196 hours.

Figure 9 (cont'd)

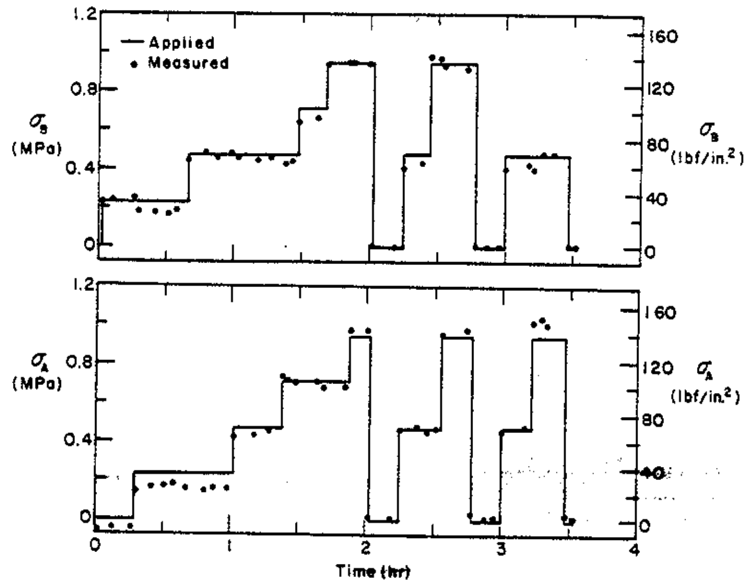


Figure 10: Measured versus applied stress for block 4.

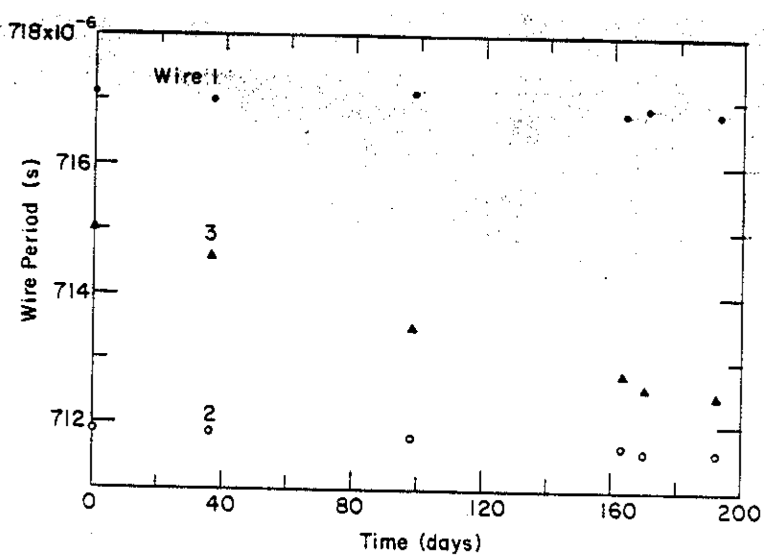


Figure 11: Variation of wire period with time for wires in biaxial ice stress sensor.

Long-Term Drift

During the course of the evaluation study, sensor readings were obtained at 20°C to examine the stability of the unloaded gauge. The period of vibration of each of the three wires in the gauge is plotted against time in Figure 11. Over a period of about 200 days, wires 1 and 2 showed a slight decrease in the wire period, while wire 3 showed a significant change.

DISCUSSION OF TEST RESULTS

The biaxial ice stress sensor has a low temperature sensitivity and the sensor response is not affected by differential thermal expansion between the ice and gauge.

The sensor output appears to vary linearly with temperature. If the sensor were in ice, the observed changes in output would correspond to stresses of about 5 kPa/°C. Relative to the resolution of the gauge (20 kPa), the temperature sensitivity is small. In many short-term applications of the gauge, temperature corrections would not be needed. However, in situations where large variations in ice temperature did occur, the sensor output would have to be corrected to obtain the highest possible accuracy.

Metge et al. (1975) postulated that the response of a steel ice stress sensor would be greatly affected by differential thermal expansion between the ice and gauge. However, the results of this investigation and those of Johnson and Cox (1980) do not support this hypothesis. If ice were an elastic material, differential thermal expansion would be a problem. Because ice creeps under low stress, localized thermal stresses in the ice around the sensor rapidly relax and are unable to build up to any significant value.

The results of the loading tests indicate that the sensor responds immediately to applied loads. In general, measured stresses are within 15% of the applied stress for both uniaxial and biaxial loading. The sensor response does not appear to be affected by ice creep and when the applied stresses are removed, the measured stresses fall close to zero. Reliable stress measurements are also obtained well beyond yielding or failure of the ice. In addition, the sensor can usually determine the direction of the applied stresses to within 5°.

Part of the observed error can be attributed to the resolution of the gauge (20 kPa) and the loading system (20 kPa). Combined, they account for about 30 kPa of the observed differences in the applied and measured stress. These differences are significant at low stress levels. Errors are also introduced by poor seating between the sides of the ice block and platens, and shear stresses on the block sides during biaxial loading. The block 3 and block 4 results show that stress measurements improve significantly when the applied stresses are held constant on the block.

If it were possible to solve the seating and shear stress problems associated with the loading machine, measured stresses would probably be within 10% of the applied stresses. This postulate is suported by the results from block 3 where a uniaxial load was maintained on the ice block. After about 3 hours, the block appears to be properly seated and the difference between the applied and measured stress is less than or equal to the combined error associated with the resolution of the gauge and loading system. Since a biaxial field can be described as the superposition of two normal uniaxial fields, the same results should be observed in a well-designed biaxial loading test where problems associated with poor seating, bulging of the ice block and shear stresses have been eliminated.

Periodic measurements under no load reveal that the sensor exhibits long-term drift. With time the strain in the vibrating wires increases, resulting in a decrease in the wire period. According to IRAD Gage, the gauge fabricator, this behavior is caused by outward displacement of the clamps holding the wires in the sensor. Work on borehole stressmeters indicates that the problem can be eliminated by heat-treating the sensor after fabrication. This was not done for the prototype sensor.

CONCLUSIONS

Reliable ice stress measurements can be obtained by measuring the diametral deformation of a stiff steel cylinder embedded in the ice. By measuring the deformation of the cylinder in three directions, we can determine both the magnitude and direction of the principal stresses in the ice. Analytical solutions describing the behavior of an elastic ring welded in an elastic plate adequately predict the sensor's inclusion factor (stress concentration factor) in ice, despite the fact that ice is a time-dependent material. Since the sensor is considerably stiffer than the ice, its deformation is not significantly affected by variations in the ice elastic modulus and by nonelastic behavior. It is not necessary to calibrate the sensor in ice.

Controlled laboratory experiments to evaluate the biaxial ice stress sensor indicate that the sensor has a low temperature sensitivity

(5 kPa/°C) and is not significantly affected by differential thermal expansion between the ice and the gauge. Loading tests of fresh water and saline ice blocks containing an embedded sensor show that the sensor has a resolution of 20 kPa and an accuracy of better than 15% under a variety of both uniaxial and biaxial loading conditions. When allowances are made for poor seating of the ice blocks in the loading machine and shear stresses on the platens, test results suggest that the sensor accuracy may be better than 10% of the applied stress. Principal stress directions can be resolved to within about 5°.

The cylindrical sensor does not greatly overload the ice and can accurately measure ice stresses well beyond ice yielding or failure. The maximum stress riser produced by the presence of the sensor in the ice is about 1.5.

The sensor is also rugged, leak-proof, and can be easily installed in an ice sheet with conventional augering equipment.

ACKNOWLEDGMENTS

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